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Correlation of the Groundwater Sapping Process in the Western Desert of Egypt and its Analogues on the Surface of Mars

Khaled Abdel-Kader Ouda

Professor Emeritus of Geology, Geology Department, Faculty of Science, Assiut University, Assiut, Egypt

ABSTRACT

The groundwater sapping process can be found in both sedimentary and volcanic rocks. This phenomenon of lateral flowing of groundwater and its emergence as seeps at the edges of the scarps required a resistant permeable layer underlain by a soft impermeable layer. Thus it can be found in Nubia Sandstone sequences of the Western Desert of Egypt which include silty or clayey horizons underlying the highly permeable sandstone beds in the Gilf El Kebir Plateau, the Dakhla Basin and the Great Sand Sea. It is also well represented on the steep shale-limestone scarps of eastern Kharga Oasis, northern scarps of Abu Tartur and Dakhla Oasis, and the eastern scarps of Farafra Oasis where the partial removal of the soft material of the underlying shale (Dakhla Shale in Dakhla or Esna Shale in Kharga and Farafra Oases) by groundwater sapping led to the creation of an overhanging ledge with protected wide alcoves above the impermeable contact between the shale and limestone. Compared to Mars, the evidence for groundwater sapping in the Western Desert of Egypt is completely identical to that of its analogues on the surface of Mars. In the latter Planet, the intensively cracked and jointed basaltic materials exposed on steep wall surfaces of the valleys as well as the amphitheater-headed valleys indicate that the basaltic cliffs were subjected to groundwater sapping process such as the sandstone and limestone scarps of the Western Desert of Egypt. Both the similarities and differences of this phenomenon between Western Desert and Mars are given.

KEYWORDS: *Groundwater sapping process, alcoves, amphitheater-headed valleys, Western Desert, Mars*

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Introduction and Previous Related Work

Groundwater sapping is an erosional process that produces major landscape features with unique characteristics (Higgins, 1982). The idea had previously been attributed to Peel (1941) based upon observations in the Gilf Kebir plateau of Libya. In this region he identified wades with flat floors and steep sides which terminated in a headward cliff and appeared to have been 'cut out from below' rather than 'let down from above'. This description succinctly summarizes the key difference between erosion by exfiltrating water and the operation of surface incision by river erosion (Nash, 1996). Since that time terrestrial valleys, gullies and depressions suggested to have been formed by groundwater erosion have been identified across a wide range of climatic settings, including systems in Hawaii (e.g. Kochel and Piper, 1986; Baker, 1990), the Colorado Plateau (e.g. Pieri et al., 1980; Laity, 1983; Laity and Malin, 1985; Baker, 1988; Howard et al., 1988), Massachusetts (Uchupi and Oldale, 1994), Japan (Onda, 1994), Libya (Peel, 1941), Egypt (Luo et al. 1997; Ouda, 2023), New Zealand (Schumm and Phillips, 1986), Botswana (Shaw and de Vries, 1988; Nash, 1992, 1995; Nash et al., 1994a,b), England (Hackness Hills, North Yorkshire, Nash,1996) and Texas (De Horn, 2020).

Valleys developed by sapping and seepage erosion are suggested by Howard et al. (1988) and Baker (1990) to have a number of distinctive morphological features which, to a certain extent, may be diagnostic of the operation of groundwater processes in their formation. These include abrupt valley initiation with amphitheater headwalls and little evidence of surface flow above the valley head, alcoves and springs in the

headward region, steep valley flanks with an abrupt angle to a flat valley floor, a long valley with a constant valley width, short first-order tributaries with possible hanging valleys and a paucity of tributaries downstream.

Malin and Edgett (2000) described the main geomorphic elements of the process of the groundwater sapping on Mars as follow: a) a theater-shaped alcove that tapers downslope, b) second channels that continue downslope from the distal apex of the alcove, and c) triangular aprons that broaden downslope and appear to be material deposited after transport through the channel system. According to these authors four types of alcoves were recognized on the surface of Mars: lengthened, widened, occupied, and abbreviated alcoves. The lengthened alcoves (A) are longer (downslope) than they are wide; where they occur in close proximity: they form characteristic badlands (B). The widened alcoves (C) are broad in transverse dimension and may include more than one smaller alcove. The occupied alcoves (D) are filled or partly filled with material that might be mobile as a unit, but not as disaggregated debris. The type examples of this form occur throughout the length of Dao Vallis. The abbreviated alcoves (E and F) show strong topographic or stratigraphic control of landform location, which limits the extent of the alcove. For example, in areas where a resistant rock unit creates an overhang, the alcove may be small or even missing.

Aharonson et al. (2002) reported that large drainage systems on Mars have geomorphic characteristics inconsistent with prolonged erosion by surface runoff. According to them the topography of these systems has not evolved to an expected equilibrium terrain form, even in areas where runoff incision has been previously interpreted. By analogy with terrestrial examples, Aharonson et al. (2002) concluded that groundwater sapping may have played an important role in the incision.

Glines and Fassett (2013) found that Nirgal Vallis (~500-km-long, ~5- km-wide) on Mars has morphological characteristics (such as amphitheater-headed tributaries) that are similar to valleys on Earth potentially formed by groundwater seepage, for example, on the Colorado Plateau, in Florida, and in Hawaii [e.g. Kochel and Piper 1986]. For this reason, Nirgal Vallis is one of the most likely candidates to have been formed by large-scale groundwater sapping on Mars (e.g. Harrison, & Grimm, 2005).

Marra et al. (2014) investigated three hydrological scenarios for valley formation on Mars: hydrostatic groundwater seepage, release of pressurized groundwater and crater-lake overflow. Valleys formed by hydrostatic groundwater seepage feature mass wasting at the valley head resulting in headward development. Further downstream, fluvial processes transport sediment in small channels. Such valleys have an amphitheater-shaped head and the depth of the valley relate to the groundwater level at the time of formation. Valley formation by this process is limited to unconsolidated, easily erodible substrates due to hydrological and fluvial transport constraints.

Marra et al. (2015) studied groundwater seepage from a distant source of groundwater and from infiltration of local precipitation in a series of sandbox experiments and combine their results with previous experiments and observations of the Martian surface According to them Louros Valles shows properties of seepage by a local source of groundwater whereas Nirgal Vallis shows evidence of a distant source, which they interpret as groundwater flow from Tharsis.

De Horn (2020) stated that the obvious places to search for alcoves anywhere on the Martian surface are stratified materials exposed on steep surfaces; amphitheater-headed valleys carved by groundwater sapping; and walls of valleys or canyons. On the Martian surface the characteristic scalloped-shaped, basaltic cliff faces formed along the valleys point to the presence of alcove roof near the slope face. The intensively cracked and jointed basaltic materials exposed on steep wall surfaces of the valleys as well as the amphitheater-headed valleys indicate that the basaltic cliffs on the surface of Mars were subjected to groundwater sapping process.

Very recently, Ouda (2023) studied both the groundwater sapping process and the runoff of old river systems in the Great Sand Sea and the Gilf El Kebir Plateau in the western part of the Western Desert. According to him the groundwater flowed through and emerged from the highly permeable steeper walls of the Nubia Sandstone (Six Hills and Sabaya formations) ridges, scarps and hillslopes at the free slope surface in the Gilf El Kebir Plateau, the Dakhla Basin at south and the Great Sand Sea at north. The main conditions controlling the groundwater sapping process include a seasonal recharge, a highly permeable trans-missive Nubia Sandstone bedrock which covers an extensive area in the Western Desert, a common development of scarps with free faces at which water can emerge, a frequent development of alcoves and headwall seepage zone almost extended along bedding planes, the undermining of sediments overlying the seepage zone and the low drainage density with short first order headwall streams that are almost running in parallelism.

Ouda (2023) noticed that the eroded quartz sandstone bed rock below the draining channels is not covered in the flat low-lying tracks by drifted loose sands which come daily from the surrounding slopes, thus suggesting recent groundwater seepage. According to this author the groundwater sapping process in the Western Desert of Egypt is ephemeral as deduced from different summer and winter field trips and from high resolution satellite images produced during the last 10 years for the same localities. In the Gilf El Kebir area Ouda (2023) found good indication that the groundwater is re-charged during winter seasons as deduced from the annual progressive enlargement of alcoves and extension of the seepage zone associated by progressive retreat of the scarp face of the cliffs and increase of undermining of the sandstone beds overlying the seepage zones.

This work concerns with the correlation of the groundwater sapping process in the Western Desert of Egypt with its analogues on the surface of Mars (Figs. 1 A-B and Fig.2).

Method of Study

The study of this phenomenon in the Western Desert of Egypt is based on both field work and remote sensing studies, using the Digital Elevation Data brought by the Shuttle Radar Topographic Mission (SRTM) of NASA's Space, 3-arc-second Resolution, version 4, satellite images and surface photography. The data covered large areas of the topographic area extending from the Gilf El Kebir at south to Siwa At north including the inhospitable and inaccessible desert of the Great Sand Sea (Ouda, 2023). The latter area includes new landforms with peculiar geologic structures (New wide depressions, plains, domes and plateaus with flat surfaces) and showing evidences of Recent groundwater seepage process beside paleodrainage networks (Fig. 3).

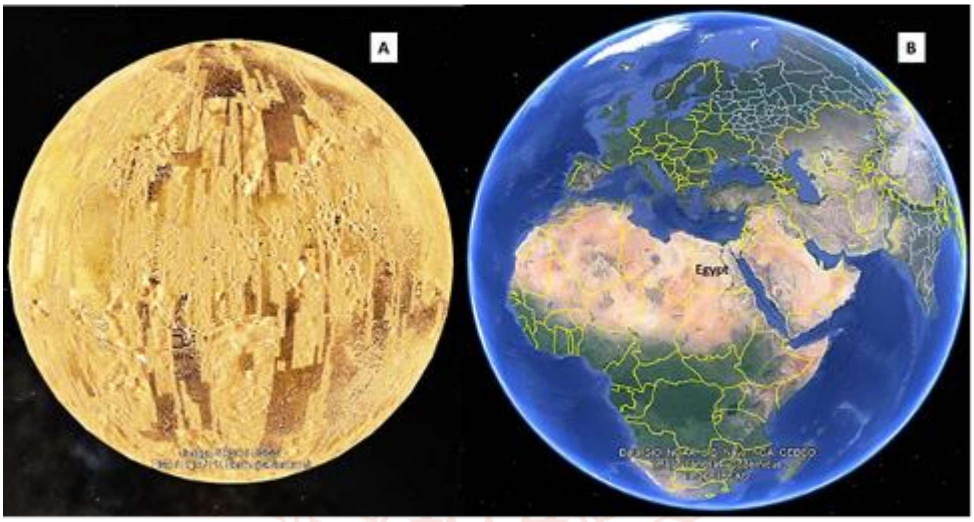

Fig.1 : Satellite images of Google Mars (A) and Google Earth Pro showing location of Egypt (B).

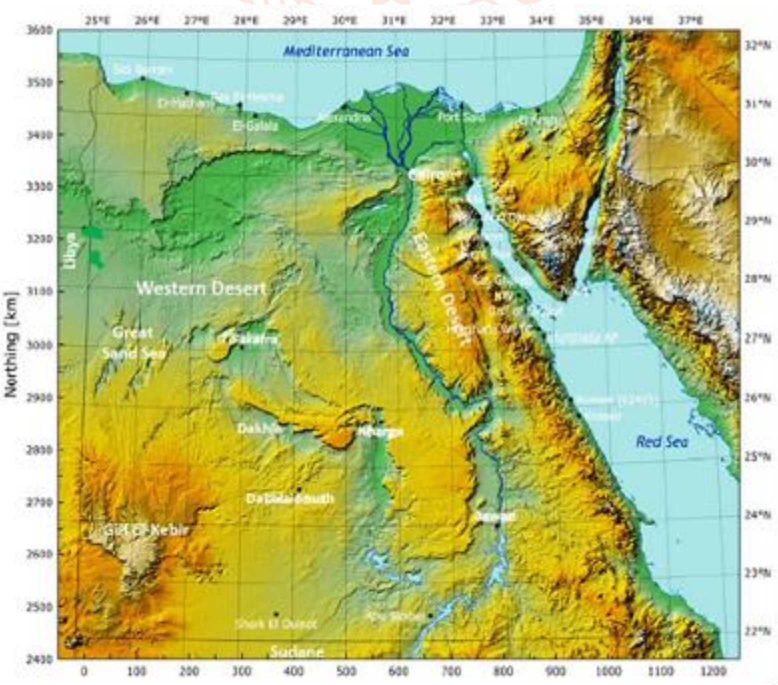

Fig.2: SRTM Map of Egypt showing areas of studies of groundwater sapping process in the Western Desert that have been compared to their counterparts on Mars.

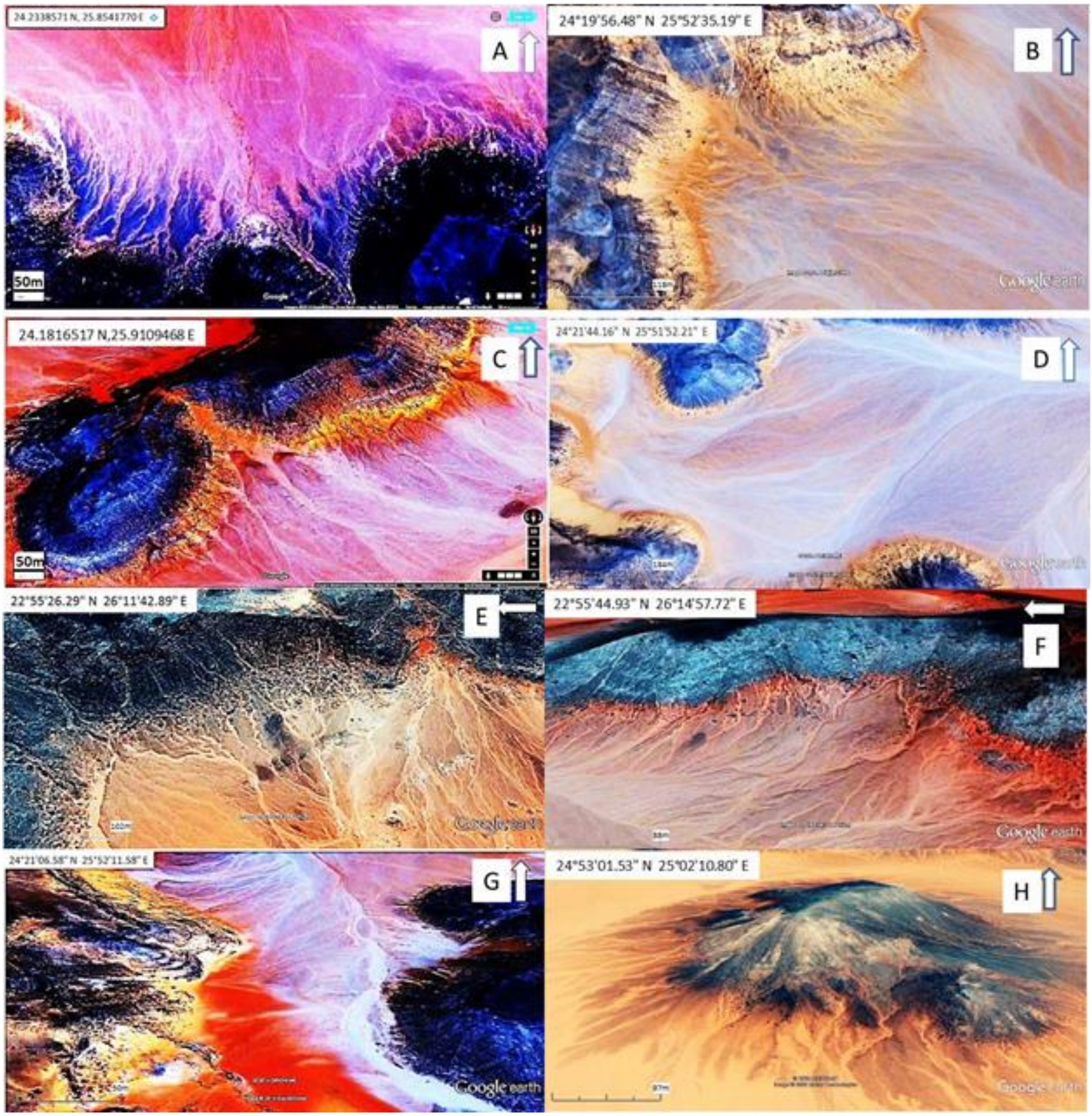

Fig. 3A-H: Satellite images from Google Earth Pro of Nubia Sandstone scarps in the Southern Great Sand Sea (A-D and G-H) and Southeastern Gilf El Kebir (E-F), Western Desert showing headwater streams made up of first to third order, more or less parallel tributaries emerged from seepage zone made up of horizontal headwall alcoves. Note the increase of the volume of groundwater which seeps through alcoves and exits frequently at and along the whole seep area leading to the retreat of the scarp face. From now and going on the arrows point to the geographic north.

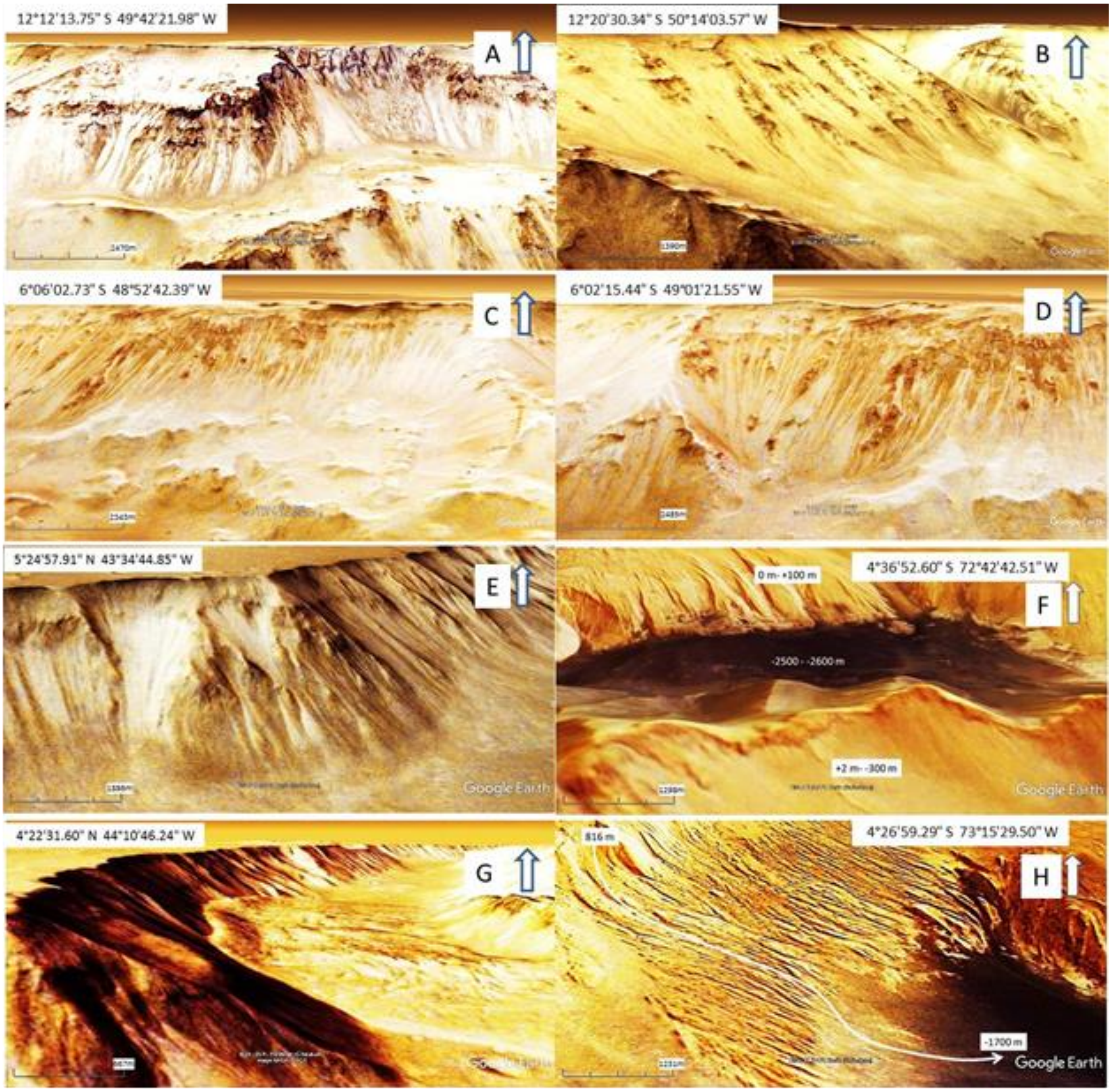

Fig. 4A-H: Satellite images from Google Mars showing strongly eroded basaltic cliffs and scarps with features of groundwater sapping process, including steep-walled, V-shaped main and secondary channels emanating from the downslope apex of the head alcove of the scarps particularly in the southern hemisphere The channels are generally starting broad and deep at their highest topographic position and taper downslope and distally. The channels would suggest the presence of sources of liquid water at shallow depths beneath the Martian surface. Note the main valleys between scarps, the intensively cracked and jointed basaltic materials exposed on steep wall surfaces of the valleys as well as the amphitheater-headed valleys which would indicate that the basaltic cliffs were subjected to groundwater sapping process

In this work, a study of the groundwater sapping process on the surface of Mars (Fig.4) is made with the aim of correlation of this phenomenon between the Western Desert of Egypt and the surface of Mars. The study is based mainly on remote sensing using high accuracy. satellite images from Google Mars, Google Map imagery and Google Earth Pro. It has been made possible by the use of Google Mars which is a program that allows exploring Mars through official satellite images gathered by different spacecraft orbiting the planet. The program is an application within Google Earth Pro which is currently the standard version of the Google Earth desktop application as of version 7.3.2.5776 (64-bit), Build Date Tuesday, March 5, 2019 12:43:51 AM UTC7.3. The program of Google Mars allows viewers to zoom around the Red Planet in much higher resolution than the simpler browser version and will even render certain locations in 3-D. It includes extremely high-resolution

images from the Mars Reconnaissance Orbiter's HiRISE camera on the NASA Mars Reconnaissance Orbiter spacecraft, the Context Camera (CTX) on NASA's Mars Reconnaissance Orbiter which offers great details with around 20 feet per pixel, the Narrow Angle Mars Orbiter Camera (MOC) on the NASA Mars Global Surveyor spacecraft, the High Resolution Stereo Camera (HRSC) instrument on the European Space Agency Mars Express spacecraft, the Compact Reconnaissance Imaging Spectrometer for Mars(CRISM) instrument on the NASA Mars Reconnaissance Orbiter spacecraft.

Results and Discussion

The alcoves resulting from the seepage of groundwater along the stratigraphic planes between highly resistant rocks, such as sandstone or limestone, and others below them with weak resistance, such as shale in the Western Desert of Egypt, are a microcosm of what is the case in basalt tuff rocks, composed of layers of different resistance, on the planet Mars. This phenomenon causes in both planets disintegration and breakdown of the bedrock and erosion of the soft impermeable beds from the slopes, causing the slopes to be undermined and undergo mass wasting. It is also the predominant mechanism of the growth of the amphitheater-headed valleys, and the exploitation of joints and fractures in the bedrock due to laterally flowing of groundwater. In addition it is responsible of formation of different types of alcoves in headwalls and seepage zones in many valley flanks. The size of these alcoves in the Western Desert ranges from 1 meter to 312 meters in length (perpendicular to the bedding planes), and from 3 meters to 760 meters in width (parallel to the bedding planes), while the size of these alcoves on Mars ranges at least from 278 meters to 11,666 meters in length, and from 40 meters to 21,393 meters in width.

Similarities

Regardless of the vast difference in the size of these alcoves between the two planets, these alcoves are similar in morphological and topographical characteristics in terms of the general shape, their horizontal and vertical extension, the primary and secondary channels that continue to descend from the distant summit of the alcove, and the general shape of the slope which resembles an amphitheater. As far as could be reached from satellite images five main types of alcoves could be distinguished in both planets:

1. **Single Individual alcoves.** These alcoves are developed separately at the head of canyons. These are formed by weakening cement by groundwater solution at the basal contact of permeable layer with an impermeable layer. The alcoves of this type have a rounded peripheries in the Gilf El Kebir, southwestern Western Desert where they are occurring at the basal contact of the Nubia Sandstone layers with underlying shale unit (Fig. 5 A, C and E). However, in Mars these alcoves have angular to subangular peripheries and occur at the contact of basaltic layers of different permeability (Fig. 5 B, D and F). In some longitudinal ridges made up of horizontally-bedded Nubia Sandstone in the Western Desert the alcoves are often developed separately in small individual openings along the contact between ridges and the ground surface. These are formed by groundwater solution at the basal contact with an impermeable shale or siltstone layer, whereas In Mars the individual alcoves are common in Louros Valles and may developed randomly as sieve openings of different sizes on the side walls of the canyon (Fig. 5 F). Very common also in both planets are the distribution of what called by Malin and Edgett (2000) “Abbreviated alcoves” which limits the extent of the alcoves (Fig. 5 G-J and Fig. 6 A-J). For example, in areas where a resistant rock unit creates an overhang, the alcove may be minute or even missing. The scarp faces in these areas are characterized by the presence of main or second channels emanating from the downslope apex of the head alcove and taper downslope and distally. The transition between the head alcove and channel are almost extended.

2. **Lengthened alcoves**. The term was introduced by Malin and Edgett (2000) on the surface of Mars to describe those alcoves which are longer (downslope) than they are wide; where they occur in close proximity, they form characteristic badlands. This type of alcoves can be distinguished in in both Western Desert of Egypt (Figs. 7 and 8 A, C, E, G and I;) and the Martian surface (Figs. 7 and 8 B, D, F, H and J) where they are composed of a massive series of long alcoves (perpendicular to the stratigraphic planes) emanating from the downslope apex of the head alcove and have short secondary channels. The individual alcove attains a length ranging from one meter to 312m and a width ranging from 3m to 760m in the Western Desert of Egypt, whereas in Mars it ranges in length from 302m to 11666 m and in width from 470m to 2630m. Massive lengthened alcoves are common in Gilf El Kebir Plateau and Dakhla Basin in the southern Western Desert as well as the Louros Valleys, Ius Chasma and Melas Chasma in Mars.

Fig. 5: Satellite images from Google Earth Pro (A, C, E and G) and Google Mars (B, D, F and H) showing correlation of single alcoves developed separately at the head of canyons in both Western Desert of Egypt and Mars. These alcoves are formed by weakening cement by groundwater solution at the basal contact of permeable layer with an impermeable layer. The alcoves of this type have a rounded peripheries in the Gilf El Kebir, southwestern Western Desert where they are occurring at the basal contact of the Nubia Sandstone layers with underlying shale unit. However, in Mars these alcoves have angular to subangular peripheries and occur at the contact of basaltic layers of different permeability, sometimes may developed randomly as sieve openings of different sizes on the side walls of the canyon (Fig. D). Abbreviated alcoves" which limits the extent of the alcoves in areas where a resistant rock unit creates an overhang, the alcove may be minute or even missing (Figs. E-H)

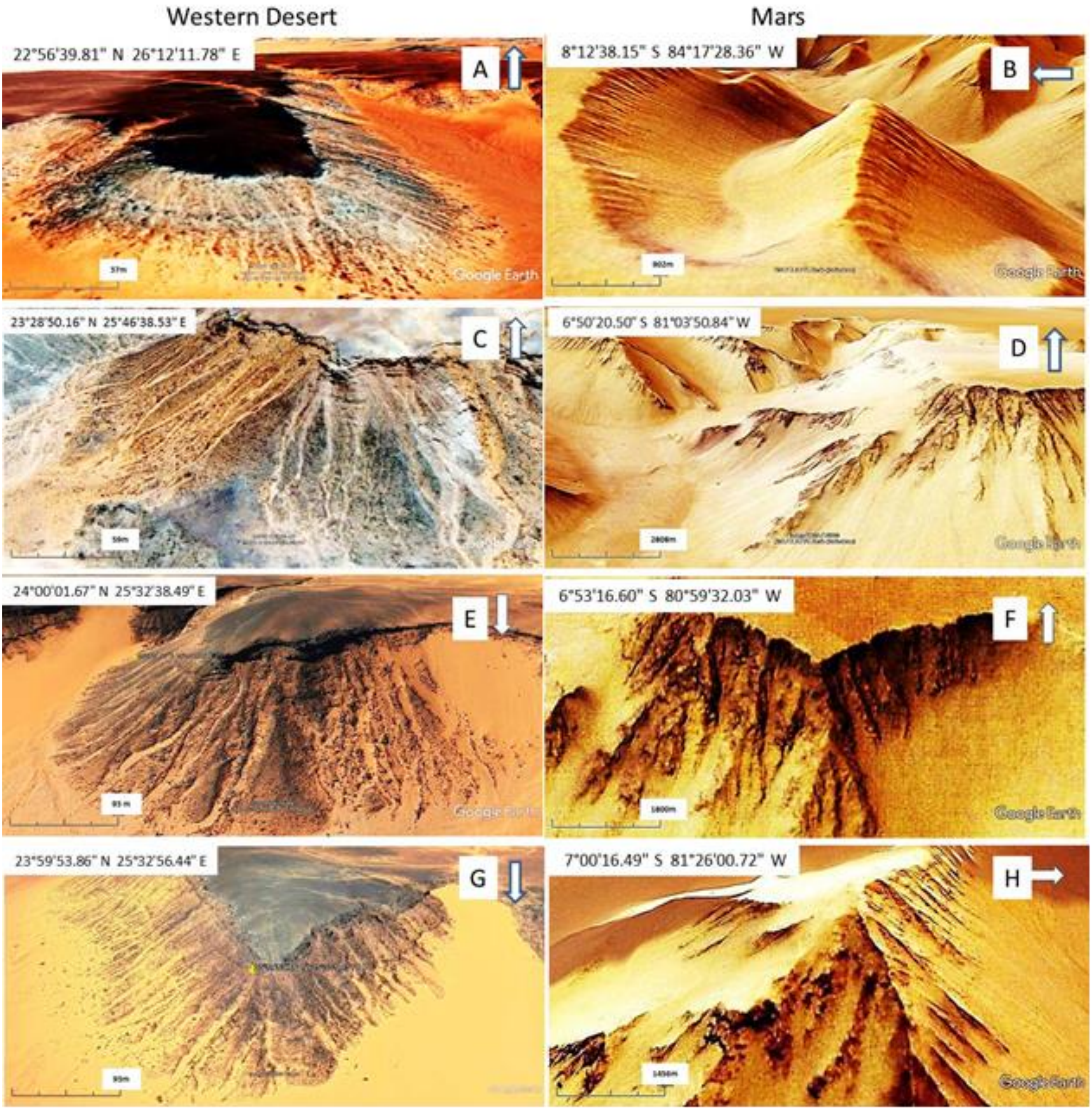

Fig. 6: Satellite images from Google Earth Pro (A,C,E, G and I) and Google Mars (B,D, F,H and J) showing correlation of additional abbreviated alcoves in both Western Desert of Egypt and Mars. These alcoves are minute or even missing. They occur in areas where a resistant rock unit creates an overhang. The scarp faces in these areas are usually characterized by the presence of main or second channels emanating from the downslope apex of the head alcove and taper downslope and distally.

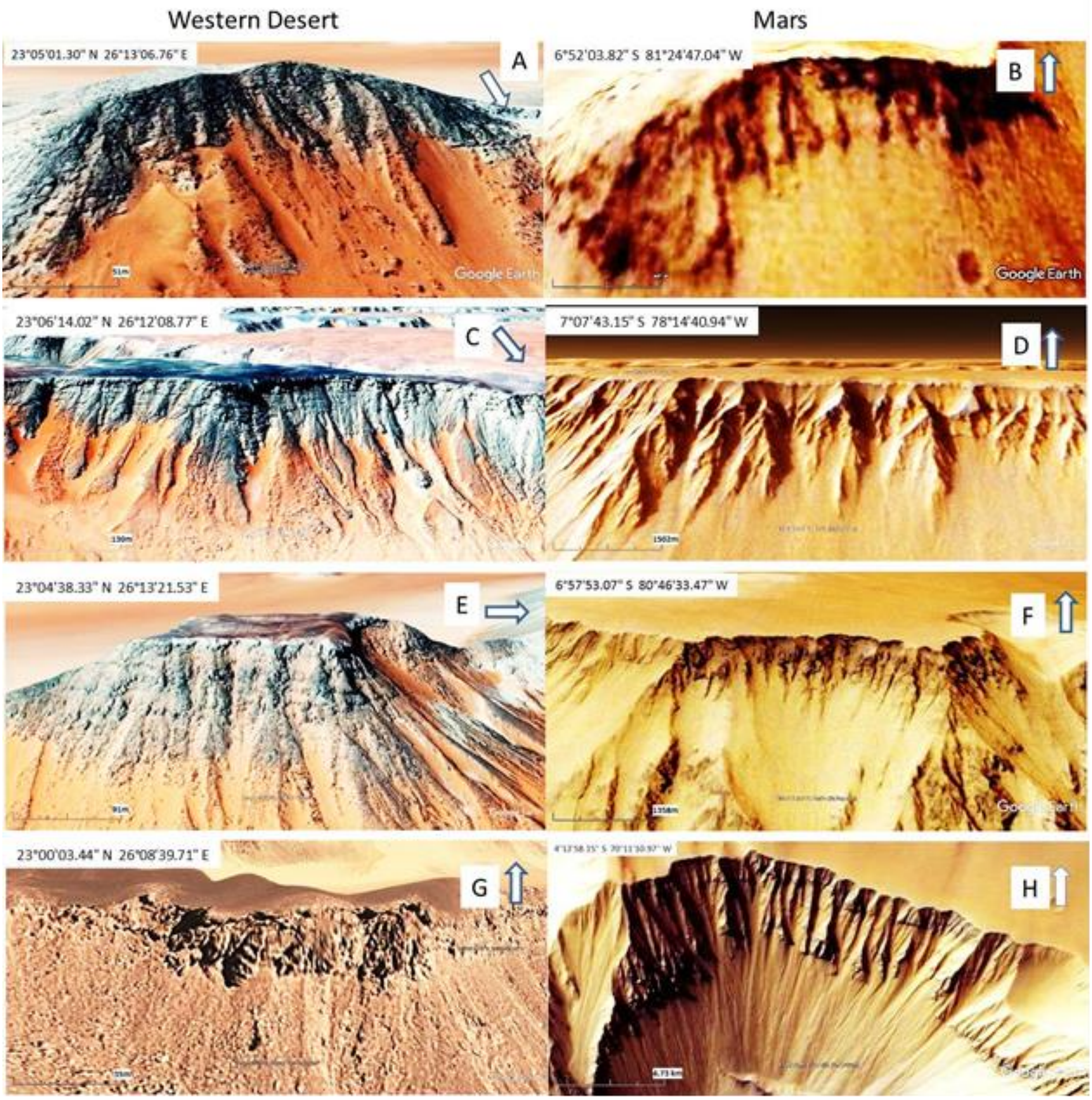

Fig. 7: Satellite images from Google Earth Pro (A, C, E and G) and Google Mars (B, D, F) showing correlation of the Lengthened alcoves between the Western Desert and Mars These alcoves are longer than they are wide along the stratigraphic planes between permeable layer with an impermeable layer. This type of alcoves can be distinguished in in both Western Desert of Egypt (southeastern and southern Gilf El Kebir) and on the Martian surface (Ius Chasma B and D, Louros Valles F, and north Candoor Chasma, H) where they are composed of a massive series of long alcoves emanating from the downslope apex of the head alcove and have short secondary channels. Look at the huge difference in the size of the alcoves between the Western Desert and Mars.

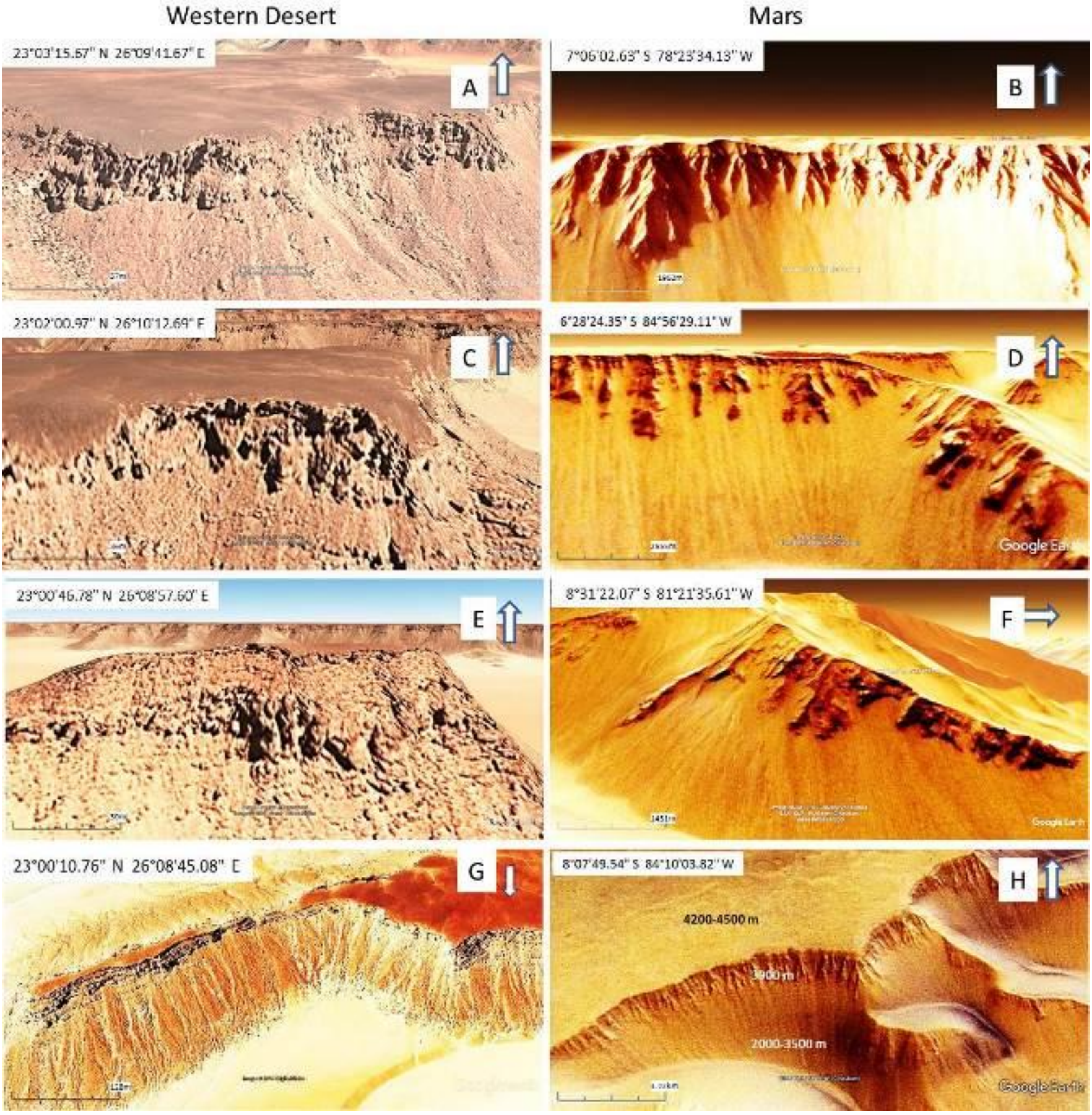

Fig. 8: Satellite images from Google Earth Pro (A, C, E and G) and Google Mars (B, D, F) showing additional Lengthened alcoves in both the Western Desert (Southern Gilf El Kebir) and Mars (Ius Chasma B and D, Louros Valles F, South of Ius Chasma H). Look at the huge difference in the size of the alcoves between the Western Desert and Mars.

3. **Connected alcoves to form arches or tunnels along the stratigraphic planes**. These alcoves are widely distributed in both the Western Desert of Egypt (Figs. 9 and 10A, C, E, G and I) and on the surface of Mars (Figs.9 and 10B, D, F, H and J). The arches and tunnels were formed due to mass collapse of slabs of the highly permeable layers as a result of groundwater seepage that promotes weathering along bedding planes and which have enough cohesion for an arch to develop. In the Nubia Sandstone scarps in the Gilf El Kebir Plateau, southwestern Egypt, the groundwater exits along the weathered bedding planes which represent the most weakened parts of the sequence and the resultant alcoves may connect together along the bedding plane to form a wide tunnel or natural arches through the horizontal or gently dipping beds of the sandstone cliffs at the northern and eastern slopes of the Gilf el Kebir Plateau as well as the Dakhla Basin.

The arches are well developed in the type sections of the Six Hills and Sabaya Formation south of the Dakhla-Kharga road (Fig. 10 A, E, and G). The length of the arches ranges between 80 m and 200 m and thus considered to be the broadest known arches in the sandstone beds (see Young et al. 2009 and Goudie, 2013). The arches have a classic elongate arch shape and all appear to be formed when the massive sandstone Formation undermined mainly by seepage of groundwater and associated salt weathering processes. In Mars, the arches and

tunnels extend for about 75 km along with the surface between the highest basaltic layer and the preceding one in the major scarp of Aromatum Chaos (Fig. 9B, D and F) as well as along plains south of Ius Chasma (Fig. 9H and Fig. 10B, D and F). Sometimes, the tunnels become associated with lengthened alcoves (Fig. 9G and H) or developed separately in wide opening extended along the contact between scarps and the ground surface (Fig. 10E-H).

4. **Widened alcoves**: The widened alcoves as identified by Malin and Edgett (2000) are broad in transverse dimension (cross-slope) and consist of more than one smaller alcove or a series of connected small alcoves focusing to a single downslope outlet. The sapped channels start broad and deep at their highest topographic position along the scarp head and taper downslope and distally, thus becoming broom-shaped (Fig.11A-H). They are common in both layered basaltic rocks on Mars (Fig. 11 B, D, F and H) and limestone cliffs in the western oases of the Western Desert (Fig.11E). They are also frequently occurring in the sandstone scarps of the Gilf El Kebir Plateau in the Western Desert (Fig.11A, C and G). The removal of the underlying weakened materials below the limestone or the basaltic layers by groundwater sapping has led to the development of scallop-shaped cliff faces formed by thinning of the alcove roof near the slope face of the limestone or the basaltic layers. The headwall seepage zone is almost extended along bedding planes where it made up of either 3 or 5 small individual alcoves. The downslope pattern in this type of alcoves consists of either a main long channel or distributary networks of small subsidiary channels.

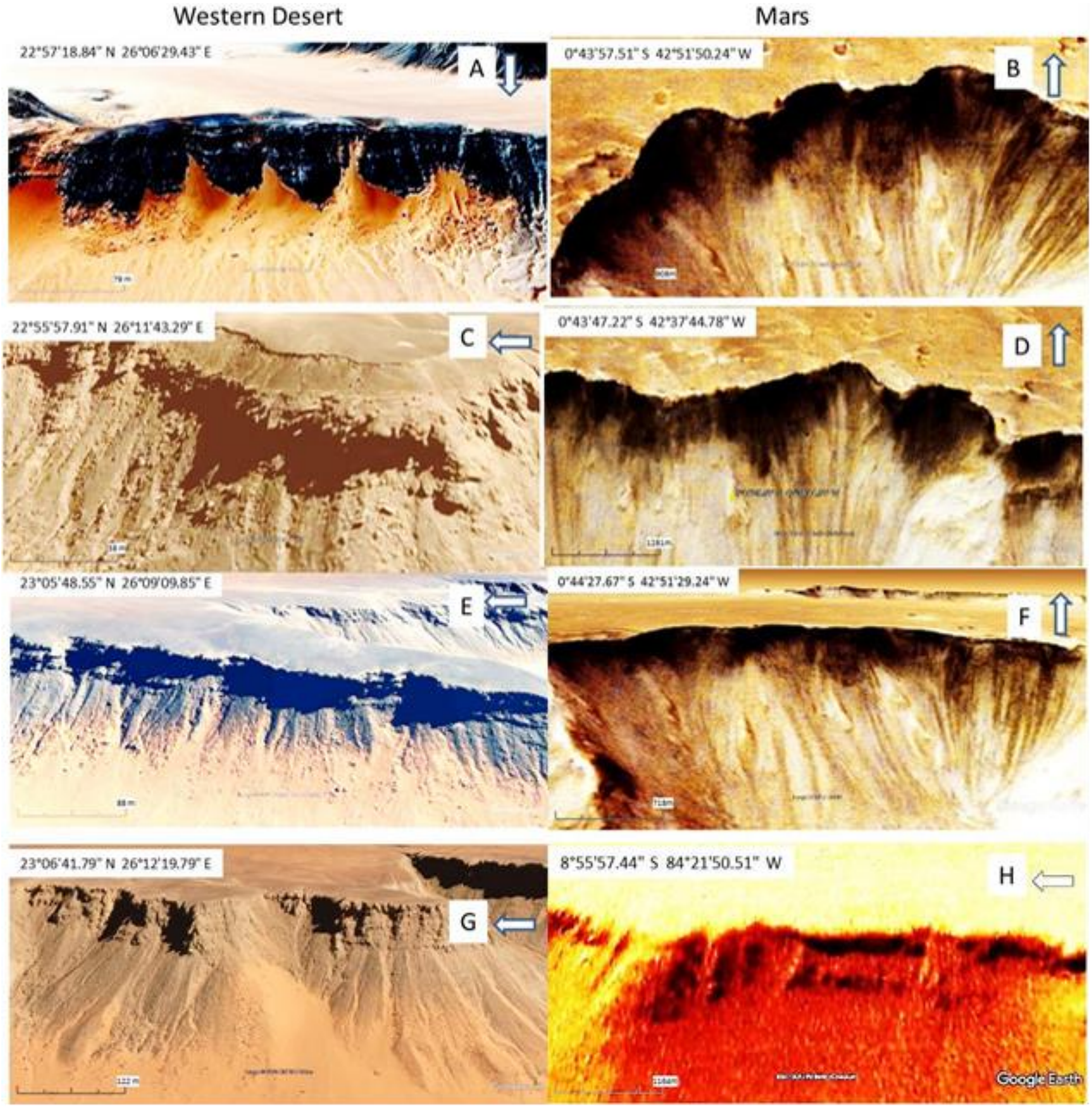

Fig. 9: Satellite images from Google Earth Pro (A, C, E, G and I) and Google Mars (B, D, F, H and J) showing connected alcoves to form arches or tunnels along the stratigraphic planes in both the Western Desert of Egypt and the surface of Mars. The arches and tunnels were formed due to mass

collapse of slabs of the highly permeable layers as a result of groundwater seepage that promotes weathering along bedding planes and which have enough cohesion for an arch to develop. The length of the arches ranges in the Western Desert of Egypt between 80 m and 200 m and thus considered to be the broadest known arches in the sandstone beds. In Mars, the arches and tunnels extend for about 75 km along with surface between the highest basaltic layer and the preceding one in the major scarp of Aromatum Chaos (B, D and F) Sometimes the tunnels become associated with lengthened alcoves (Figs. G from Gilf El Kebir in the Western Desert while Fig. H is from South of Ius Chasma in Mars).

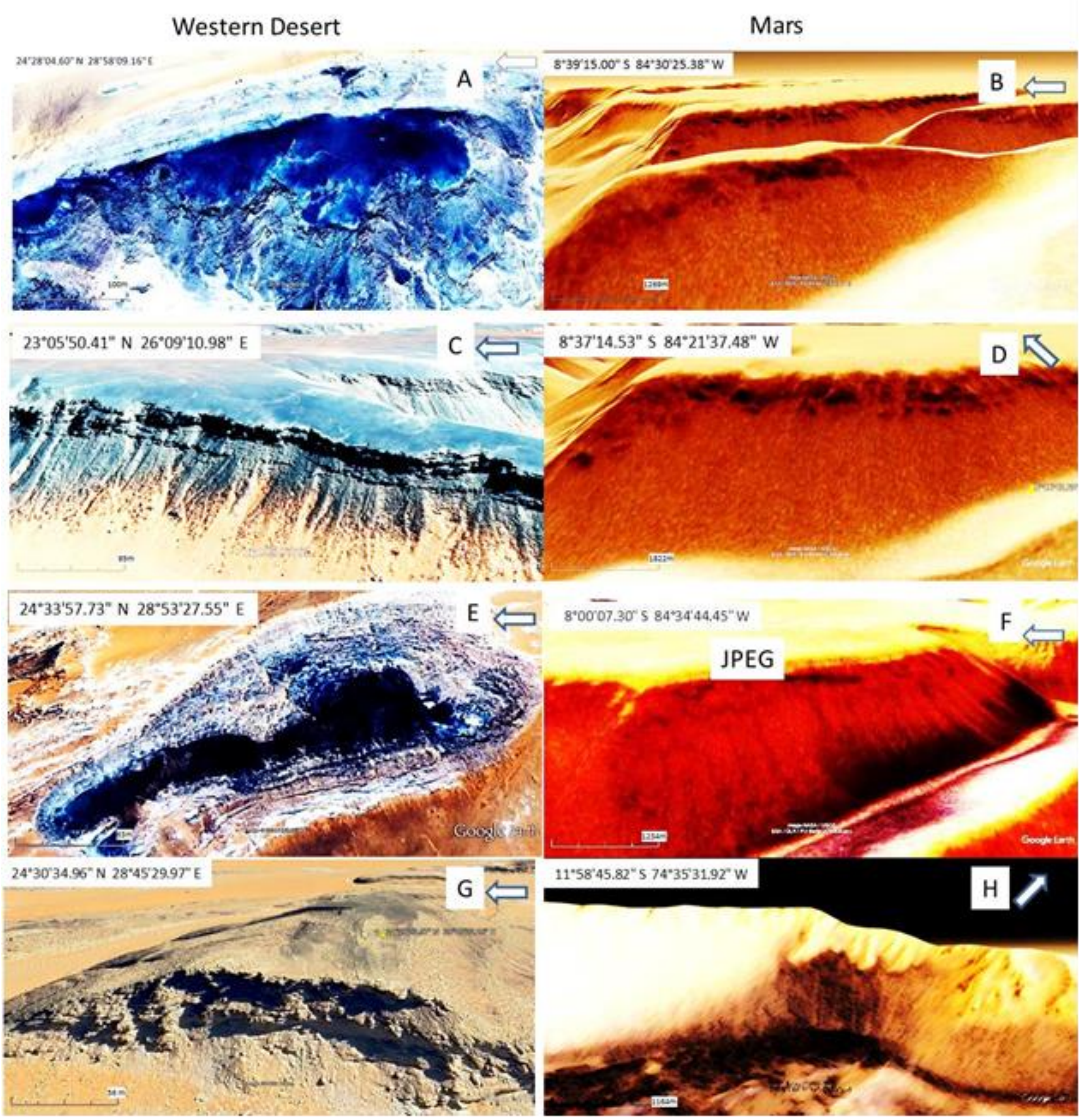

Fig. 10: Satellite images from Google Earth Pro (A, C , E and G) and from Google Mars (B, D, F and H) showing additional connected alcoves to form tunnels along the stratigraphic planes in both Western Desert and Mars. Figs. A, E and G are from the Nubia Sandstone in the Dakhla Basin while Fig. C from north of the Gilf El Kebir. Figs. B, D and F are from the plains south of Ius Chasma on the surface of Mars, while Fig. H from south Melas Chasma in Mars. Note that the alcoves may be developed in wide openings extended along the contact between scarps and the ground surface (Figs. E and G from Dakhla Basin, and Figs. F and H from South of Ius Chasma and south of Melas Chasma respectively). Note also the huge difference in the size of the alcoves between the Western Desert and Mars.

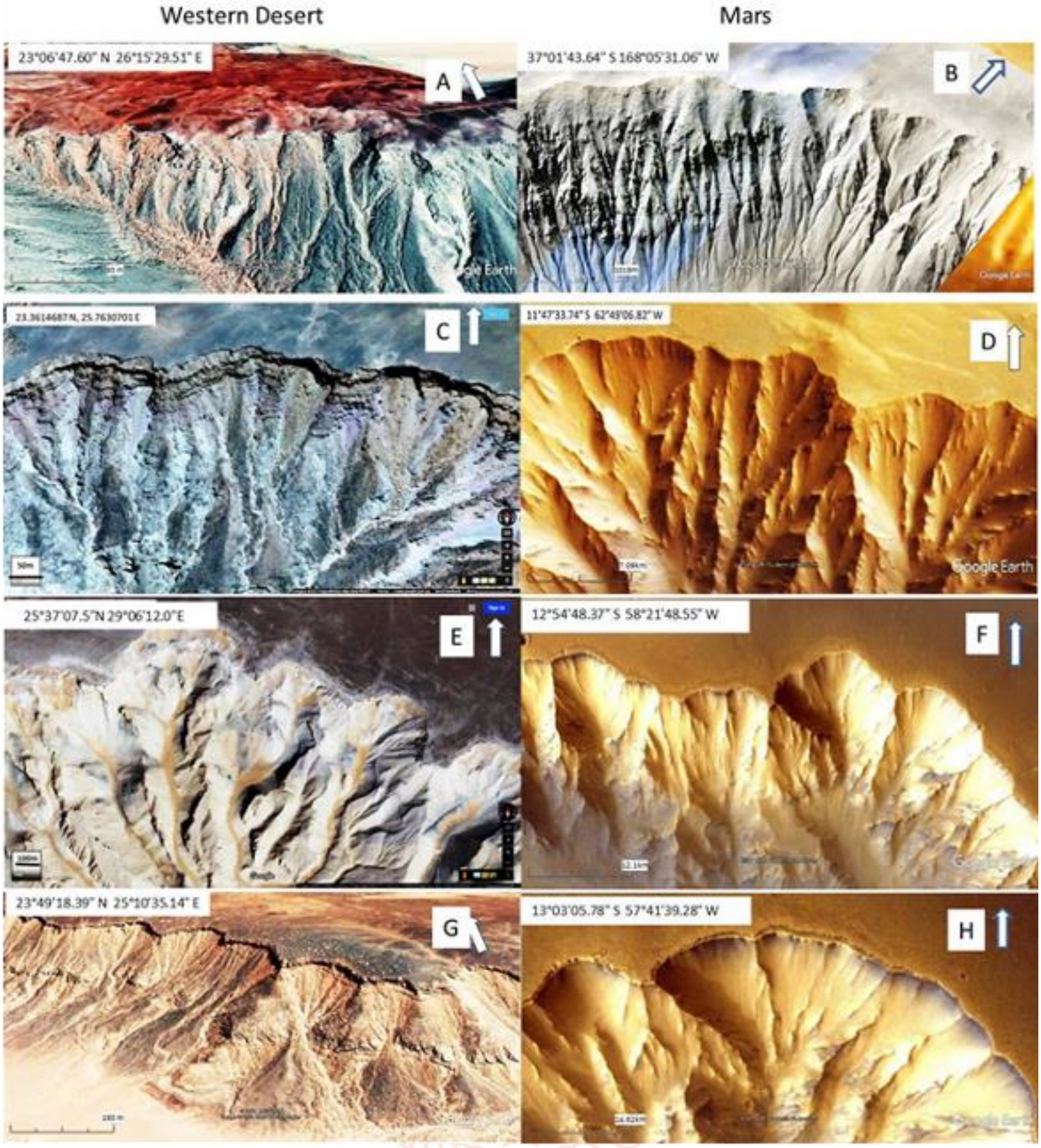

Fig. 11: Satellite images from Google Earth Pro (A, C, E and G) and Google Mars (B, D, F and H) showing widened alcoves which are broad in transverse dimension (cross-slope) and consist of more than one smaller alcove or a series of connected small alcoves (abbreviated alcoves) focusing to a single downslope outlet in both the Western Desert of Egypt and the surface of Mars. The sapped channels start broad and deep at their highest topographic position along the scarp head and taper downslope and distally, thus becoming broom-shaped. The removal of the underlying weakened materials below the limestone or the basaltic layers by groundwater sapping has led to the development of scallop-shaped cliff faces formed by thinning of the alcove roof near the slope face of the limestone or basaltic scarps. Figs. A, C and G are from the Gilf El Kebir Plateau while E from Dakhla Oasis Western Desert. On the Martian surface the characteristic scalloped-shaped, basaltic cliff faces (Figs.B, D, F and H) are widely distributed along the Valleys Marineris and the Louros Valleys

On the steep scarps of eastern Kharga Oasis, northern scarps of Abu Tartur and Dakhla Oasis and the eastern scarps of Farafra Oasis, the partial removal of the less resistant material of the underlying shale (Dakhla Shale in Dakhla (Fig.11E) or Esna shale in Kharga and Farafra Oases) by groundwater sapping led to the creation of an overhanging ledge with protected wide alcoves above the impermeable contact between the shale and limestone. The removal of the underlying shale materials by groundwater sapping has also led to the development of scallop-shaped cliff faces near the slope face of the Thebes Limestone in Kharga and Farafra scarps, or Tarawan Chalk in Dakhla and Abu Tartur scarps. This type of wide alcoves can also be traced in Nubia Sandstone sequences which include silty or clayey horizons underlying the highly permeable sandstone beds along the

scarps of the Gilf El Kebir Plateau. It attains a length ranging from 165m to 400 m and a width reaching up to 450 m.

On the Martian surface the characteristic scalloped-shaped, basaltic cliff faces are widely distributed along the Valles Marineris where they extend for more than 1250 km and also along the Louros Valles where they extend for more than 730 km. The individual scallop-shaped cliff face in Mars attains a width of 4.5 km and a length ranging from 6.44 to 7.25 km of where they point to the presence of alcove roof made up of 5-6 alcoves near the slope face. The intensively cracked and jointed basaltic materials exposed on steep wall surfaces of the valleys as well as the amphitheater-headed valleys indicate that the basaltic cliffs were subjected to groundwater sapping process such as the limestone scarps of the Western Desert Oases.

5. **Lateral expanding alcoves to form large caves of varying size and shape scattered randomly along the mountain slope**. The main conditions controlling the groundwater sapping process of this type of alcoves in the Western Desert include a seasonal recharge, a highly permeable trans-missive Nubia Sandstone bedrock which covers an extensive area in the Western Desert, and a common development of scarps with free faces at which water can emerge (Fig. 12A, C, E and G). In the Gilf El Kebir area there is good indication that the groundwater is re-charged during winter seasons as deduced from the annual progressive enlargement of alcoves and extension of the seepage zone associated by progressive retreat of the scarp face of the cliffs and increase of undermining of the sandstone beds overlying the seepage zones. The length of these alcoves in the Gilf El Kebir ranges between 45m and 134m while the width ranges between 244m and 400 m.

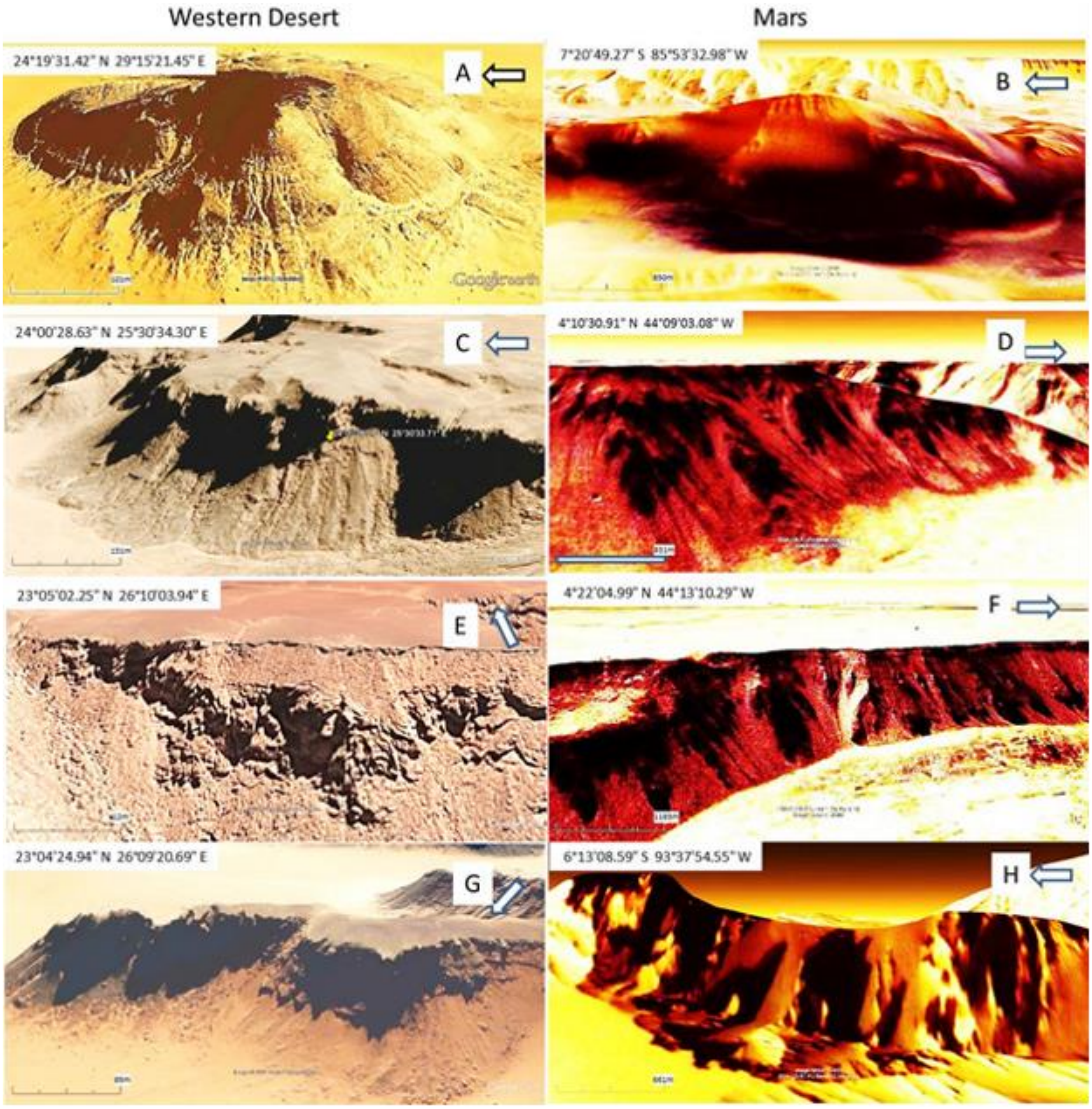

Fig. 12: Satellite images from Google Earth Pro (A, C, E and G) and Google Mars (B, D, F and H) showing Lateral expanding alcoves to form large transverse cavities of varying size and shape which

are randomly scattered along the mountain slope in both Western Desert and Mars. The main conditions controlling the groundwater sapping process of this type of alcoves in the Western Desert include a seasonal recharge, a highly permeable trans-missive Nubia Sandstone bedrock, and a common development of scarps with free faces at which water can emerge. The length of these alcoves in the Gilf El Kebir , Western Desert ranges between 45m and 134m while the width ranges between 244m and 400 m. In Mars the random expanding alcoves along the scarp slope are widely distributed along Shalbatana Valles (394 km long). The individual caves attain a width varying from 2630m to 3529m and a length varying from 2412m to 2770m.

Fig. 13: Satellite images from Google Earth Pro (A, C, E and G) and Google Mars (B, D, F and H) showing Amphitheater-headed valleys carved by groundwater sapping process in the both the Western Desert and Mars . Fig. G-H: Cross sections along the sandstone scarps west of Gilf El Kebir , Western Desert and basaltic cliffs along Ius Chasma on Mars

In Mars the random expanding alcoves along the scarp slope are widely distributed along Shalbatana Valles (394 km long). The individual caves attain a width varying from 2630m to 3529m and a length varying from 2412m to 2770m (Fig. 12B, D, F and H). This may support a repeated seepage due to recharge in these valleys accompanied by removal of talus accumulated at the base of the slope as deduced from the progressive enlargement of alcoves and random extension of the seepage zone associated by progressive retreat of the canyon head and sidewalls.

The groundwater sapping process produces major landscape features with unique characteristics in both the western Desert of Egypt and Mars. The emerging of the groundwater at seeps gradually removes materials from the headwall and slopes, thus leading to the undermining of the overlying sediments. The undermining of the overlying sediments of the sandstone, limestone or basalt cliff will cause retreat of the scarp face (canyon head). The resultant week rock debris shatter readily upon impact then becoming easily affected by weathering process and ultimately accumulated at the foot of the cliff. Repeated seepage due to recharge accompanied by removal of talus accumulated at the base of the slope will lead to successive retreat of the canyon head and sidewalls hence the development of an amphitheater-headed valley before eventual collapse (Fig. 13A-H).

Differences

It has been noted by Ouda (2023) that the alcoves resulting from groundwater seepage in the Western Desert of Egypt change their shape, horizontal and vertical extension, as well as depth with the seasons of the year. They are small, limited in extent, and shallow in depth during the summer due to increased rates of evaporation and decreased recharge rates. However, in the winter, the alcoves grow in size, expand more and become deeper as a result of increased groundwater flow rates and weak evaporation rates.

The increase of the volume of groundwater which seeps through alcoves and exits frequently at and along the whole seep area during winter has led to the retreat of the scarp face and thus undermining of the overlying sandstone which falls to the valley floor below. However, no sediments at the bottom of the slopes are found in the Western Desert as a result of the continuous annual flow of water (despite the variation in recharge rates depending on the seasons), which does not allow the accumulation of erosion products at the bottom of the slope (Fig. 14A, C , E and G). Rather, these sediments spread in the main valleys away from the slope. Thus, it can be stated that the difference in volume of the water which seeps out from alcoves seem to be not only controlled by porosity and permeability of the wall rock of the hill, or quantity of water soaked into ground in the hill but also by the climatic regimes and rates of evaporation which are minimized in winter and maximized in summer.

As for the planet Mars, it is not possible to determine the relationship between the size of these alcoves and the change of the annual seasons. However, it can be deduced from the enormous size of these alcoves, which range from hundreds of meters to several thousands of meters, as well as their wide spread along the slopes of the valleys that extend from 394 km to 1256 km that these alcoves were formed through extensive groundwater recharge of the layers of basalt tuff with varying porosity during an earlier period in the geological history of the planet Mars. This nutrition did not continue recently to this day, as is the case in the Western Desert, but rather dried up a long time ago. This is evidenced by the presence of dense rock debris at the bottom of the basalt slopes in Mars (except of some valleys like Shalbatana Valles), as a result of the accumulation of the products of erosion of the basaltic layers, thus confirming the weakness of the emergence of groundwater over time on the one hand, and the hardness of the rocks and the inability to transport clastic products from the valleys on the other hand (Figs. 14B, D and F).

This is also evidenced by the shallowness of the main and secondary gullies in March (Fig. 14H), which emerge from the top of the slope in the head gap to the bottom of the slope. Such a shallowness is not compatible with the vertical thickness of the slope (6.83-8.3 km). While the main and secondary channels emanating from the top of the slope to the bottom of the slope in the Western Desert are deeper and clearer in the sandstone hills of the Western Desert although the thickness of the slopes above the valleys does not exceed 229-310 meters (Fig. 14G).

On the other hand, the main valleys between the slopes in the Western Desert (Fig. 15A, C, E, F and H) are considerably wide with respect to the height of slopes due to the continued flow of groundwater through the alcoves throughout the year until the present time despite it varies in quantity according to the annual seasons. Meanwhile, the main valleys between the slopes on Mars are relatively narrow as regards to the huge height of the outcrops (Fig. 15B, D, F and G). This is most probably due to the slow infiltration of groundwater through the alcoves during time and the weak flow of groundwater on the slopes due to their extreme hardness. This causes the process of erosion of the surface of the slope to slow down and thus the weak rate of its return to the back and the expansion of the valleys. Meanwhile

Thus, it can be stated that the alcoves in March could be compared to their winter counterparts in the Western Desert in terms of shape, horizontal and vertical extension, as well as in terms of the general shape of the slope that resembles an amphitheater, but it cannot be compared to the summer alcoves in the Western Desert which exhibit much less size and extension as a result of less flowing of groundwater along the seep zone (Fig. 16A-O). However, evidence of the continued charging of the alcoves with recent groundwater is not available on the

slopes of the basalt mountains on the surface of Mars, except for the alcoves extending laterally along the mountain slopes of some valleys such as the Shalbatana Valley, where evidence of flooding with groundwater is available, like its winter counterparts in the Western Desert.

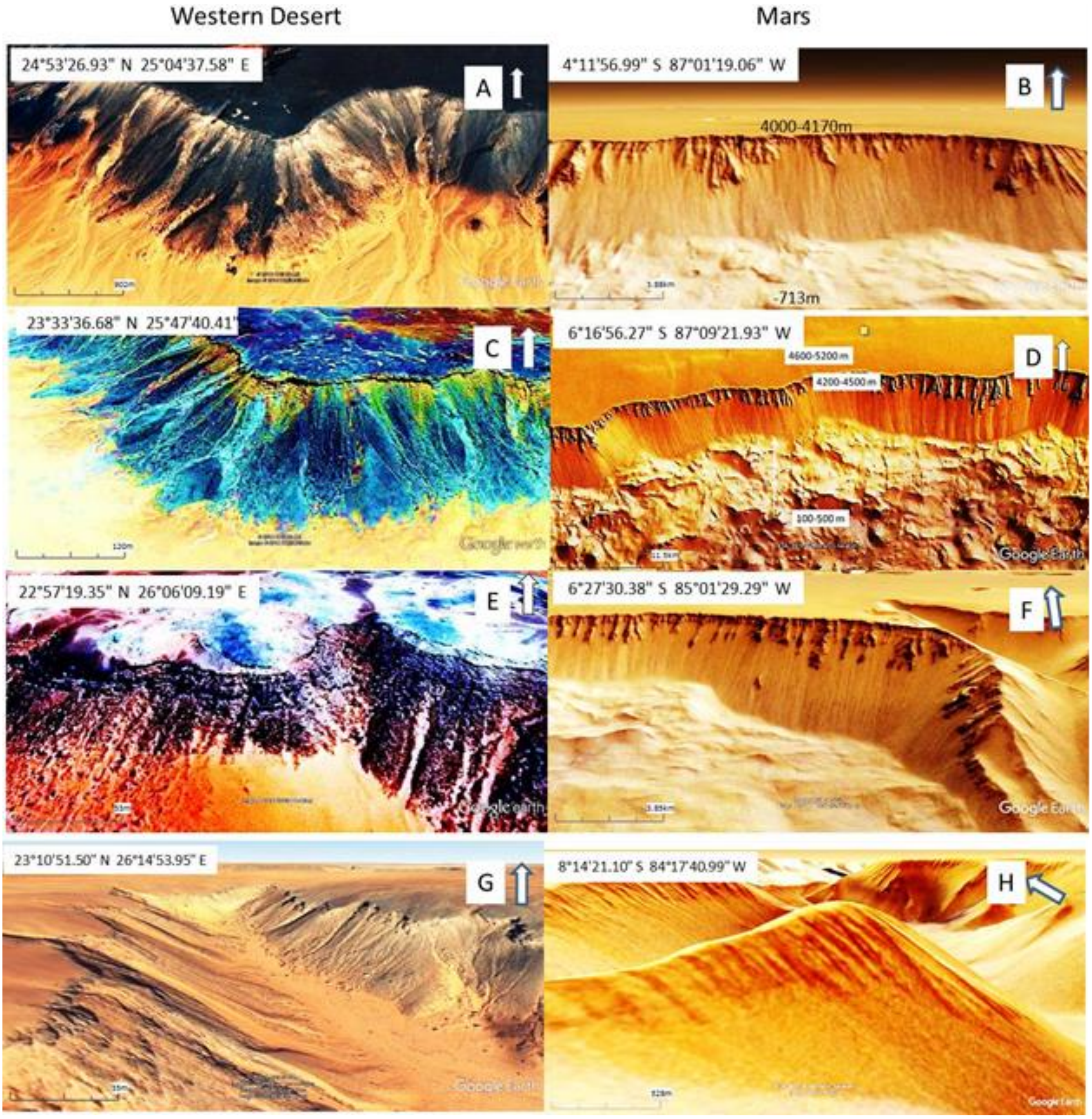

Fig. 14: Satellite images from Google Earth Pro (A, C , E and G) and Google Mars (B, D, F and H) showing that no sediments at the bottom of the slopes are found in the Western Desert as a result of the continuous annual flow of water (despite the variation in recharge rates depending on the seasons), which does not allow the accumulation of erosion products at the bottom of the slope. However, In Mars dense rock debris occur at the bottom of the basalt slopes as a result of the accumulation of the products of erosion of the basaltic layers, thus confirming the weakness of the emergence of groundwater over time on the one hand, and the hardness of the rocks and the inability to transport clastic products from the valleys on the other hand. Figs. G-H : showing the difference in depth of the main gullies between the slopes of the Western Desert and Mars. Note that these gullies are deeper in the western Desert while become very shallow in Mars despite the huge height of the slope.

Fig. 15: Satellite images from Google Earth Pro (A, C , E and G) and Google Mars (B,D, F and H) showing difference in width of valleys with respect to height of scarps between the Western Desert and Mars. Despite the huge size of the slopes of cliffs of Mars, the main valleys between these slopes are relatively narrow with respect to the height of slopes. This is due to the slow infiltration of groundwater through the alcoves or the weak flow of groundwater on the slopes due to their extreme hardness, which causes the process of erosion of the surface of the slope to slow down and thus the weak rate of its return to the back and the expansion of the valleys.

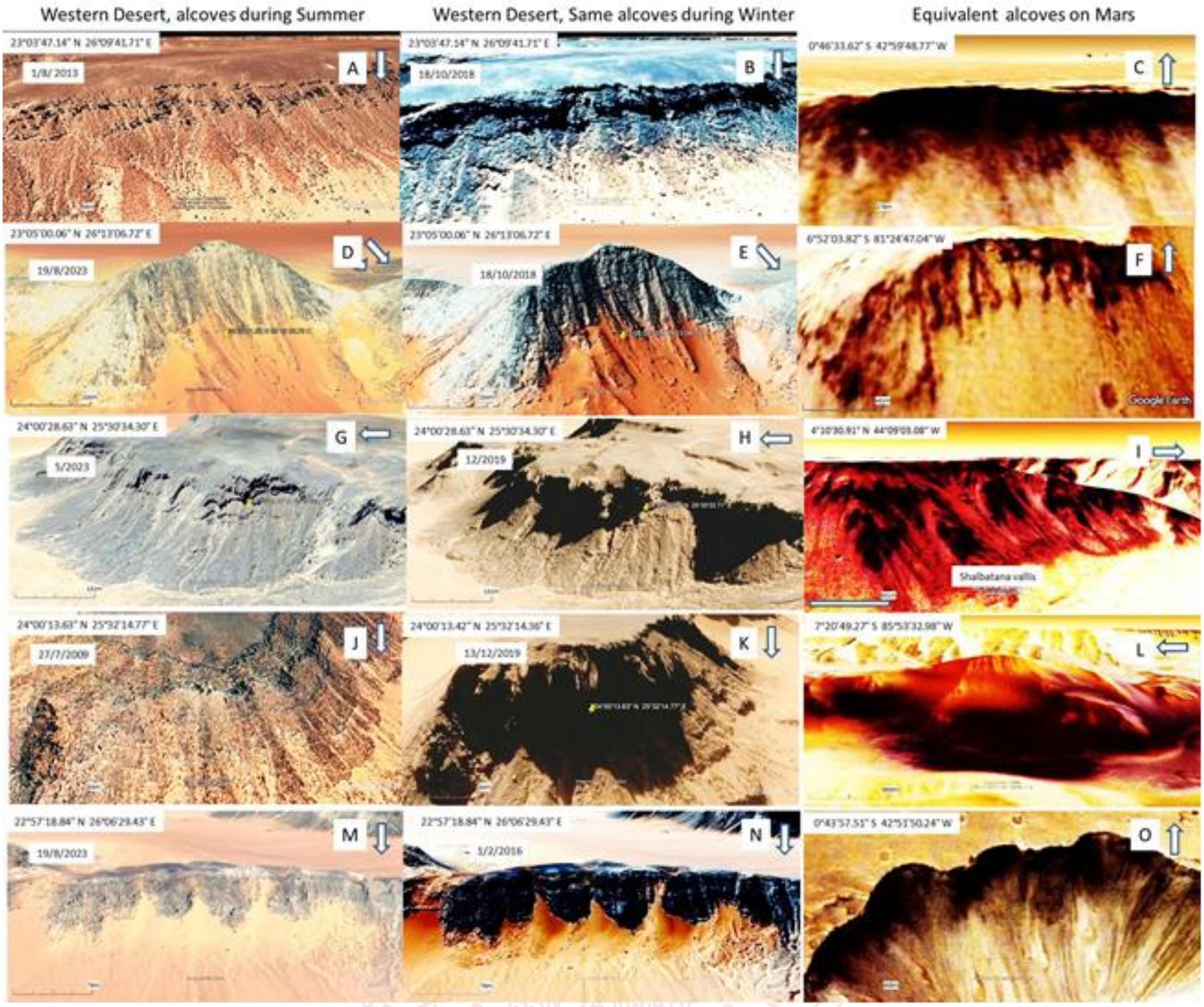

Fig. 16: Satellite images from Google Earth Pro (AB, DE , GH, JK and MN) and Google Mars (C, F, I, L and O) showing correlation between summer alcoves, winter alcoves in the Western Desert and their counterparts in Mars. Note that alcoves in March could be compared to their winter counterparts in the Western Desert in terms of shape, horizontal and vertical extension, as well as in terms of the general shape of the slope that resembles an amphitheater, but it cannot be compared to the summer alcoves in the Western Desert which exhibit much less size and extension as a result of less flowing of groundwater along the seep zone. Note also the vast difference in the size of alcoves between the Western Desert and Mars.

Conclusion

The alcoves resulting from the seepage of groundwater along the stratigraphic planes between highly resistant rocks, such as sandstone or limestone, and others below them with weak resistance, such as shale in the Western Desert of Egypt, are a microcosm of what is the case in basalt tuff rocks, composed of layers of different resistance, on the planet Mars. This phenomenon causes in both planets disintegration and breakdown of the bedrock and erosion of the soft impermeable beds from the slopes, causing the slopes to be undermined and undergo mass wasting. It is also the predominant mechanism of the growth of the amphitheater-headed valleys, and the exploitation of joints and fractures in the bedrock due to laterally flowing of groundwater. In addition it is responsible of formation of different types of alcoves in headwalls and seepage zones in many valley flanks. The size of these alcoves in the Western Desert ranges from 1 meter to 312 meters in length (perpendicular to the bedding planes), and from 3 meters to 760 meters in width (parallel to the bedding planes), while on the surface of Mars, the alcoves resulting from the phenomenon of groundwater sapping process reach enormous sizes ranging from 278 meters to 11,666 meters in length, and from 40 meters to 21,393 meters in width.

Regardless of the vast difference in the size of these alcoves between the two planets, these alcoves are similar in morphological and topographical characteristics in terms of the general shape, their

horizontal and vertical extension, the primary and secondary channels that continue to descend from the distant summit of the alcove, and the general shape of the slope which resembles an amphitheater. As far as could be reached from satellite images from Google Earth Pro and Google Mars, five main types of alcoves could be distinguished in both planets:

1. Single Individual alcoves developed separately at the head of canyons. These are formed by weakening cement by groundwater solution at the basal contact of permeable layer with an impermeable layer. Very common also in both planets are the distribution of the so-called “Abbreviated alcoves” which limits the extent of the alcoves
2. Lengthened alcoves. These alcoves are composed of a massive series of long alcoves (perpendicular to the bedding planes) emanating from the downslope apex of the head alcove and have short secondary channels.
3. Connected alcoves to form arches or tunnels along the stratigraphic planes were formed due to mass collapse of slabs of the highly permeable layers as a result of groundwater seepage that promotes weathering along bedding planes and which have enough cohesion for an arch to develop
4. Widened alcoves which are broad in transverse dimension (cross-slope) and consist of more than one smaller alcove or a series of connected small alcoves focusing to a single downslope outlet. The sapped channels start broad and deep at their highest topographic position along the scarp head and taper downslope and distally. The removal of the underlying weakened impermeable layer below a resistant permeable layer by groundwater sapping has led to the development of scallop-shaped cliff faces formed by thinning of the alcove roof near the slope face of the sandstone, limestone or the basaltic layers.
5. Lateral expanding alcoves which form large caves of varying size and shape scattered randomly along the mountain slope. The main conditions controlling the groundwater sapping process of this type of alcoves include a seasonal recharge, and a common development of scarps with free faces at which water can emerge.

It is noted that the alcoves resulting from groundwater seepage in the Western Desert of Egypt change their shape, horizontal and vertical extension, as well as depth with the seasons of the year. They are small, limited in extent, and shallow in depth during the summer due to increased rates of evaporation and decreased recharge rates. However, in the winter, the alcoves grow in size, expand more and become deeper as a result of increased groundwater flow rates and weak evaporation rates. The repeated seepage due to recharge has led to successive retreat of the canyon head and sidewalls hence the development of an amphitheater-headed valley. However, no sediments at the bottom of the slopes are found in the Western Desert as a result of the continuous annual flow of water (despite the variation in recharge rates depending on the seasons), which does not allow the accumulation of erosion products at the bottom of the slope. Rather, these sediments spread in the main valleys away from the slope.

As for the planet Mars, it is not possible to determine the relationship between the size of these alcoves and the change of the annual seasons. However, it can be stated that the alcoves in March could be compared to their winter counterparts in the Western Desert in terms of shape, horizontal and vertical extension, as well as in terms of the general shape of the slope that resembles an amphitheater. Thus, it can be deduced from the enormous size of these alcoves in Mars, which range from hundreds of meters to several thousands of meters, as well as their wide spread along the slopes of the valleys that extend from 394 km to 1256 km that these alcoves were formed through extensive groundwater recharge of the layers of basalt tuff with varying porosity during an earlier period in the geological history of the planet Mars. This nutrition did not continue recently as is the case in the Western Desert, but rather dried up a long time ago. This is evidenced by the presence of dense rock debris at the bottom of the basalt slopes in Mars (except of some valleys like Shalbatana Valles), as a result of the accumulation of the products of erosion of the basaltic layers, thus confirming the weakness of the emergence of groundwater over time on the one hand, and the hardness of the rocks and the inability to transport clastic products from the valleys on the other hand.

It is also evidenced by the shallowness of the main and secondary gullies in March which emerge from the top of the slope in the head gap to the bottom of the slope. Such a shallowness is not compatible with the vertical thickness of the slope. Also, the main valleys between the slopes in Mars are relatively narrow as regards to the huge height of the scarps, thus confirming the slow infiltration of groundwater through the alcoves during time and the weak flow of groundwater on the slopes due to their extreme hardness, which causes the process of erosion of the surface of the slope to slow down and thus the weak rate of its return to the back and the expansion of the valleys.

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References

[1] Aharonson O., Zuber Maria T., Rothman D. H., Schorghofer N., Whipple K. X., (2002). Drainage basins and channel incision on Mars. Earth, Atmospheric, and Planetary Sciences, 99 (4) 1780-1783. https://doi.org/10.1073/pnas.261704198.

[2] Baker, V. C., 1988. Evolution of valleys dissecting volcanoes on Mars and Earth. In: Howard, A. D., Kochel, R. C., and Holt, H. E., eds., Sapping features of the Colorado plateau, a comparative planetary geology field guide: Washington D. C., National Aeronautics and Space Administration Special Publication 491, 96–97.

[3] Baker, V. C., 1990. Spring sapping and valley network development, with case studies by Kochel, R. C., Baker, V. R., Laity, J. E., and Howard, A. D. In: Higgins, C. G., and Coates, D. R., eds., Groundwater geomorphology: The role of subsurface water in earth-surface processes and landforms: Geological Society of America Special Paper 252: 235–265.

[4] De Hon R. A. , 2020. Martian Alcoves as Havens from Harsh Surface Environment. 3rd International Planetary Caves 2020 (LPI Contrib. No. 2197) https: //www.hou.usra.edu/meetings/3rdcaves2020/pdf/1030.pdf

[5] Glines N. H., Fassett1 C. I., 2013. Evidence for groundwater sapping on Mars from junction angles of Nirgal Vallis tributaries. 44th Lunar and Planetary Science Conference (2013), 2011 pdf

[6] Goudie A. S., 2013. Arid and Semi-Arid Geomorphology. Cambridge University Press; 1 edition (2013-05-27). https://doi.org/10.1017/CBO9780511794261

[7] Harrison K.P., Grimm R. E., 2005. Groundwater-controlled valley networks and the decline of surface runoff on early Mars. J Geophys Res 110:E12S16. doi:10.1029/2005JE002455

[8] Higgins C. G., 1982. Drainage systems developed by sapping on Earth and Mars. Geology, 10: 147-152.

[9] Howard, A. D., Kochel, R. C., and Holt, H. E., eds., 1988. Sapping features of the Colorado plateau, a comparative planetary geology field guide: Washington, D.C., National Aeronautics and Space. Administration Special Publication 491.

[10] Kochel R. C., Piper J. F., 1986. Morphology of large valleys on Hawaii: Evidence for groundwater sapping and comparisons with Martian valleys. Journal of Geophysical Research: Solid Earth (1978–2012) 91 (B13): E175–E192, 30 DOI: 10.1029/JB091iB13p0E175

[11] Laity J. E., 1983. Diagenetic contolos on groundwater sapping and valley formation, Colorado Plateau, revealed by optical and electron microscopy. Physical Geography, 4 (2): 103-125.

[12] Laity J. E., Malin M. C., 1985. Sapping processes and the development of theater-headed valley networks on the Colorado Plateau. Bull. Geological Society of America, 96 (2): 203-217.

[13] Luo W., Arvidson R. E., Sultan M., Becker R., Crombie, M. K., Sturchio N., El Alfy Z., 1997. Ground-water sapping processes, Western Desert, Egypt. Geological Society of America Bulletin 1997;109;43-62, DOI: 10.1130/0016-7606(1997)109<0043:GWSPWD>2.3.CO;2

[14] Malin M. C. , Edgett K. S., 2000. Evidence for Recent Groundwater Seepage and Surface Runoff on Mars. Science 288 (5475), 2330-2335 DOI: 10.1126/science.288.5475.2330

[15] Marra, W. A., Braat L., Baar A. W.,. Kleinhans M. G., 2014. Valley formation by groundwater seepage, pressurized groundwater outbursts and crater-lake overflow in flume experiments with implications for Mars. Icarus 232 (2014) 97–117.

[16] Marra W. A., McLelland S. J., Parsons D. R., Murphy B. J., Hauber E., Kleinhans M. G., 2015. Groundwater seepage landscapes from distant and local sources in experiments and on Mars. Earth Surf. Dynam., 3, 389–408, doi:10.5194/esurf-3-389.

[17] Nash D. J.,1992. The development and environmental significance of the dry valleys (mekgacha) in the Kalahari, central southern Africa. Unpublished PhD thesis University of Sheffield.

[18] Nash D. J.,1995. Structural control and deep weathering in the evolution of dry valley

systems of the Kalahari, central southern Africa. Africa Geoscience Review, 2: 9-23.

[19] Nash, D. J., 1996. Groundwater sapping and valley development in the Hackness hills, north Yorkshire, England. Earth surface processes and landforms, 21: 781-795 (1996).

[20] Nash D. J., Thomas D. S. G., Shaw P.A., 1994a. timescales, environmental change and dryland valley development. In: A. C. Millingron and K. Pye (eds): Environmental change in drylands. Wiley Chichester,: 25-41.

[21] Nash D. J., Shaw P.A., Thomas D. S. G., 1994b. Duricrust development and valley evolution process-landform links in the Kalahari. Earth Surface Processes and landforms 19, 299-317.

[22] Onda Y., 1994. Seepage erosion and its implication in the formation of amphitheater valley head: a case study in Obara, Japan. Earth Surface Processes and Landforms 19, 627-640.

[23] Ouda, A-K Kh., 2023. Groundwater Sapping Process and Runoff of Old River Systems in the Great Sand Sea and the Gilf El Kebir Plateau, Western Desert of Egypt. International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, 7 (5), 181-234,URL www.ijtsrd.com/papers/ijtsrd59885.pdf

[24] Peel R. F., 1941. Denudational landforms of the central Libyan Desert. Journal of Geomorphology 4 (1):3-23.

[25] Pieri D.C., 1980. Marine Valleys: Morphology, distribution, age and origin. Science, 210:895-897.

[26] Schumm S. A., Phillips L., 1986. Composite channels of the Canterbury Plain, NewZealand. a Martian analog? Geology, 14: 326-329.

[27] Shaw P.A., De Vries J.J., 1988. Duricrust, groundwater and valley development in the Kalahari of southeast Botswana. J. Arid Environ., 14 , 245-254

[28] Uchupi, E., and Oldale, R. N., 1994. Spring sapping origin of the enigmatic relict valleys of Cape Cod and Martha’s Vineyard and Nantucket Islands, Massachusetts: Geomorphology, 9, 83–95.

[29] Young A. P., Guzaa R.T., Flicka R.E., O'Reilly W.C., Gutierrez R., 2009. Rain, waves, and short-term evolution of composite seacliffs in southern California. Marine Geology 267, 1–7, doi:10.1016/j.margeo.2009.08.008